ARES

Astromaterials Research & Exploration Science

ANNUAL REPORT 2001

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Astromaterials Research and Exploration Science Office

Carl B. Agee, Ph.D., Director
http://ares.jsc.nasa.gov/

The Astromaterials Research and Exploration Science (ARES) Office at NASA Johnson Space Center (JSC) conducts astromaterials curation and basic research in earth, planetary, and space sciences. ARES staff also participates in robotic planetary missions and supports human space flight aboard the Space Shuttle and International Space Station (ISS). The newly formed ARES Office, which has its heritage in the former Earth Science and Solar System Exploration Division, performs the physical science efforts of the JSC Space and Life Sciences Directorate.

JSC is a Center of Excellence for Astromaterials (samples of other bodies in our solar system) and has been responsible for curation of the precious Apollo lunar samples since 1969. The Lunar Sample Facility and other curation cleanrooms are unique NASA resources. Our curation efforts are greatly enhanced by a strong group of planetary scientists who conduct peer-reviewed astromaterials research. ARES is also a charter member of the NASA Astrobiology Institute, a virtual research institute studying the origin of and search for life in the universe. JSC is a world leader in orbital debris research, including modeling, monitoring, and designing debris shielding. ARES earth scientists manage the database of astronaut photography that is predominantly from Shuttle and ISS missions, but includes the results of 40 years of human space flight. Because of our position as the planetary science group at the human space flight center, ARES has been active in supporting planning for future human exploration of the Moon and Mars.

ARES is organized into three offices (see figure 1): Astromaterials Research (SR), Astromaterials Acquisition and Curation (ST), and Human Exploration Science (SX). Each has multiple research goals and functions. SR staff conducts basic research in astromaterials and astrobiology and shares the results through education and outreach. ST staff manages curation of current astromaterials collections, plans for future collections, and conducts basic research. SX staff conducts research in earth science and space debris, supports shuttle and ISS missions, and plans for future human exploration of the Moon and Mars.

ARES

ASTROMATERIALS RESEARCH & EXPLORATION SCIENCE

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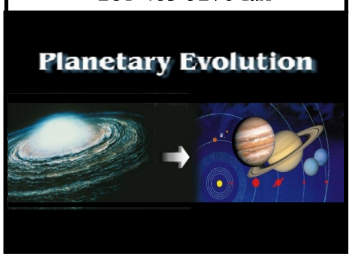


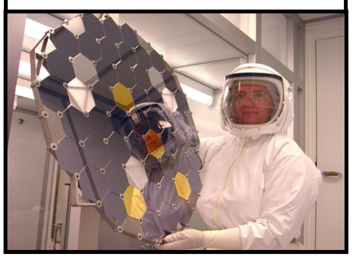
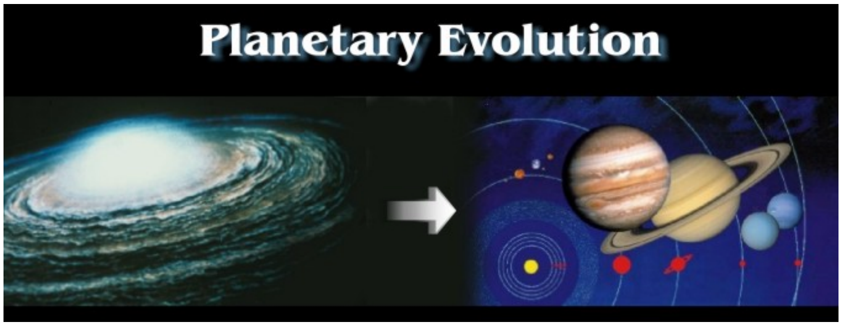



Figure 1. Astromaterials Research and Exploration Organization Chart

During 2001, ARES staff and visitors comprised about 200 people, most of whom are scientists and engineers. Staff member backgrounds cover essentially all of the physical sciences (physics, chemistry, astronomy, geology), plus biology, mathematics, computer science, and engineering. ARES permanent staff includes 45 civil servants. Of these, 36 are scientists and engineers, 30 of who have doctorates. Lockheed Martin, ARES primary support contractor, employs about 100 people, in predominantly scientific positions. Approximately 50 academic visitors conducted research projects at ARES in collaboration with our staff. These included 17 postdoctoral fellows, mostly National Research Council postdocs, who are at JSC for two year periods. Summer visitors who stayed from one to three months included 7 university faculty members, 20 university students, and 6 secondary school teachers. Supplementing its long-term civil servant and contractor staff with academic visitors provides new insights to our research and gives ARES staff an opportunity to train the next generation of space scientists. In addition to JSC visitors, ARES scientists participate in many collaborations with scientists across the country and around the world.

This Annual Report summarizes programs in each of our offices. Several specific projects are described for each office. It also includes a brief report on our extensive education and outreach activities. It concludes with lists of publications, awards, and personnel.



Astromaterials Research Office (SR)

Gordon A. McKay, Ph.D., Manager
http://ares.jsc.nasa.gov/AstroResearch/intro.html

The staff of the Astromaterials Research Office conducts peer-reviewed research in astromaterials and astrobiology. Scientists are funded through basic science disciplines of the NASA ROSS NRA (http://research.hq.nasa.gov/code_s/nra/current/NRA-02-OSS-01/index.html), particularly Cosmochemistry, but also Origins, Exobiology, Planetary Geology, and Planetary Astronomy. Further funding comes from the NASA Astrobiology Institute (http://nai.arc.nasa.gov/) and planetary mission, instrument development, and data analysis programs.

The fundamental goals of our research are to understand the origin and evolution of the solar system and the nature and distribution of life in the solar system. Our research involves analysis of, and experiments on, astromaterials in order to understand their nature, sources, and processes of formation. Our state-of-the-art analytical laboratories include four electron microbeam labs for mineral analysis, four spectroscopy labs for chemical analysis, and four mass spectrometry labs for isotopic analysis. Other facilities include the experimental impact laboratory and both one-atmosphere gas mixing and high-pressure experimental petrology labs. Recent research has emphasized a diverse range of topics, including

- study of the solar system's primitive materials such as carbonaceous chondrites and stratospheric dust
- study of early solar system chronology using short-lived radioisotopes
- study of large-scale planetary differentiation and evolution through study of siderophile element partitioning and isotopic systematics
- study of the petrogenesis of Martian meteorites through petrographic, isotopic, chemical, and experimental melting studies
- interpretation of remote sensing data, especially from current robotic Mars missions, through study of terrestrial analog materials
- study of the role of biological systems in evolution of astromaterials

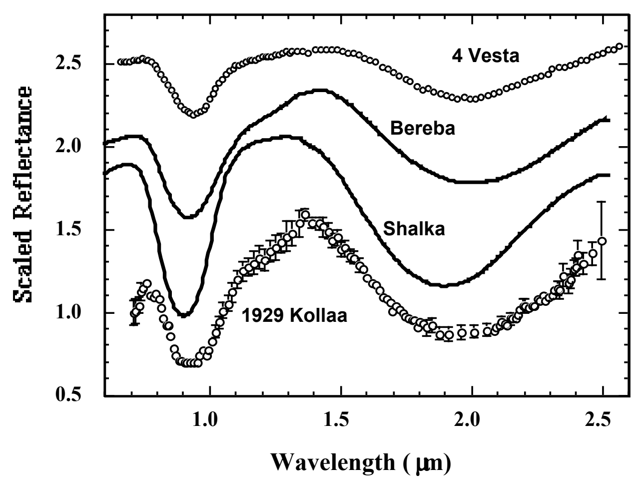
The following reports give examples of astromaterials research done by members of this and other ARES offices.

Research in Planetary Astronomy

Faith Vilas, Kandy S. Jarvis, Michael Kelley, and Susan M. Lederer

The ARES Planetary Astronomy Group works primarily with ground-based spectrophotometric data of asteroids, comets, and other small bodies. These data permit classification of asteroid types and in some cases, analysis of the mineralogy of their surfaces. Recent work by group members includes the discovery of a relationship between 4 Vesta, 1929 Kollaa and a group of meteorites. The astronomy team also is participating in a Japanese/US sample-return mission to near-Earth asteroid 25143. Asteroid studies not only help us understand the formation and evolution of small planetary bodies, but through their link with meteorites, to the early history of the solar system as a whole. These studies also provide vital information for future impact mitigation or space resource utilization efforts.

In March 2001, Astronomy team members working at the NASA Infrared Telescope Facility observed asteroid 1929 Kollaa, which has an orbit very similar to that of asteroid 4 Vesta. Subsequent analyses of the spectra for Kollaa showed that its mineralogical composition is a precise match to that of Vesta. Furthermore, it was a nearly perfect match to a subset within a group of basaltic meteorites, the HED's, which were also derived from Vesta. This was the first discovery of a mineralogical link between 4 Vesta and any other asteroid, and the first link between the HED meteorites and any asteroid other than Vesta. Asteroid 1929 Kollaa probably was ejected from the outermost layer, the crust, of 4 Vesta during a giant impact that left a 400 km crater at Vesta's south pole. Since Kollaa is about 14 km in diameter, the crust on Vesta must be at least 14 km thick to have accommodated a fragment of that size. This is the first real estimate of the



An IRTF scaled reflectance spectrum of 4 Vesta is compared with spectra of 1929 Kollaa and two HEDs meteorites, Bereba and Shalka. This is the first time an asteroid's spectrum has proven to match spectra of 4 Vesta or any HEDs meteorite.

crustal thickness on Vesta and will be useful in modeling the asteroid's thermal evolution. Asteroid 4 Vesta is one the targets of NASA's upcoming Discovery mission, DAWN.

The MUSES-C spacecraft mission, a Japanese (ISAS) and United States (NASA) cooperative effort, will rendezvous with and obtain a sample of near-Earth asteroid 25143 (1998 SF36), with the intention of returning the sample to Earth for study (see curation report). In March 2001, asteroid 25143 made its closest approach to Earth prior to the MUSES-C launch. An extensive ground-based observing campaign was conducted at telescopes in Hawaii, Arizona, and Texas. The astronomy team collected more than 500 spectra covering nearly the entire surface of the asteroid. These spectra are supplying critical information about the geological composition of the asteroid and offer an opportunity to calibrate the spacecraft instruments with real data from the target. The data also provide an idea of the material properties with which the sampling mechanism must contend, whether there are planetary protection issues involved, and the effect of viewing geometry on the data. Early results of the ground-based study were presented to the MUSES-C team in October 2001.

"Short-lived" Nuclei and a Precise Chronology for the Early Solar System

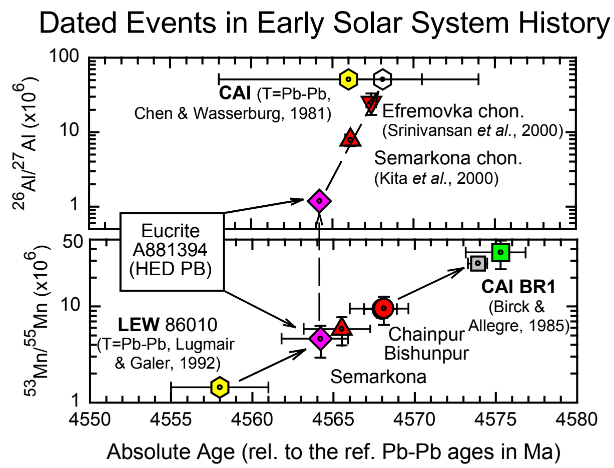
Laurence E. Nyquist, Chi-Yu L. Shih, and Henry Wiesmann

Geochronology is the science of determining the ages of rocks from measurement of parent/daughter isotopes in radioactive decay. Different isotope systems are used for dating different rocks and distinct events based on the half-lives of radioactive decay and the ages of events being dated. Thus carbon dating (half-life ~6000 years) is used to date young rocks, especially fossils. Isotopes of potassium, rubidium, samarium and uranium (half-lives in billions of years) are used to date formation ages of ancient rocks: Most meteorites 4.5 billion years; Moon rocks 4.5-3.0 billion years; Mars meteorites 4.5 billion-170 million years; Earth rocks ~4 billion - present.

This project uses "short-lived" or extinct isotopes to date relative ages of meteorites, the most ancient rocks. Extinct isotopes are isotopes that were present at solar system formation, but have totally decayed to their radiogenic daughter isotopes. The ones used in this study (aluminum and manganese) have half-lives of about a million years. By measuring the relative amounts of daughter isotopes in meteorites formed by accretion, differentiation, and volcanism it is possible to obtain a chronology of the early solar system.

Measurements of aluminum (Al) and manganese (Mn) isotopes were made in the ARES Thermal Ionization Mass Spectrometry Laboratory. Samples studied include two achondrites (reference sample angrite LEW86010 and eucrite A881394) and chondrules from three primitive chondrites (Semarkona, Chainpur and Bisunpur). Results are plotted in the figure below relative to the precisely determined Pb-Pb age of LEW86010 (4.558 billion years). Data from other studies are also included in the figure.

The initial relative abundances of extinct radioisotopes ^{26}Al (half-life 0.7 million years) and ^{53}Mn (half-life 3.7 million years) are inferred from measured increases in daughter isotopes ^{26}Mg and ^{53}Cr respectively. These are then plotted relative to amounts of stable isotopes ^{27}Al and ^{55}Mn. Mn data are plotted relative to the absolute age of the LEW86010 angrite, then Al data use the A881394 eucrite as a secondary standard. The eucrite, likely formed by volcanism on asteroid 4 Vesta, is 6 million years older than the angrite from another differentiated asteroid. The parent asteroid for the eucrite may have accreted with relative ^{26}Al abundance several times that in the rock itself. If so, ^{26}Al decay could have been the source of heat for melting the asteroid, and causing volcanism to its surface. The chondrules, which formed during accretion, are about 4 million years older than the eucrite and calcium aluminum inclusions (CAI), which are the most primitive meteorite components and contain tiny presolar grains, are the oldest solar system materials. This use of "short-lived" isotopes shows that formation of the early solar system took place very quickly – over a span of just twenty million years.

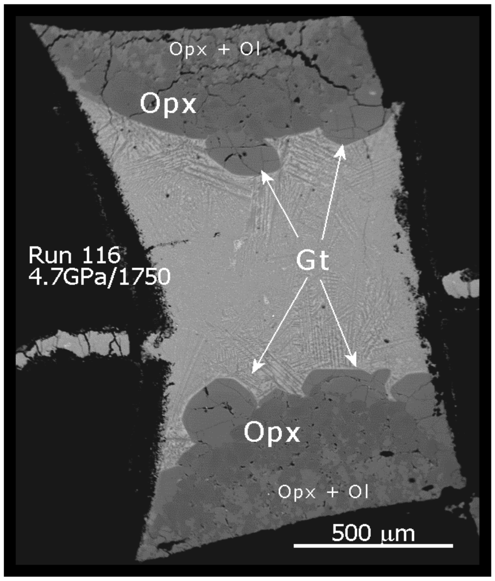


A relative chronology for the early solar system referenced to the eucrite Asuka 881394.

Research in High Pressure Experimental Petrology

Carl B. Agee, David S. Draper, Dimitris M. Xirouchakis, Nancy Chabot, and Laura Gilpin

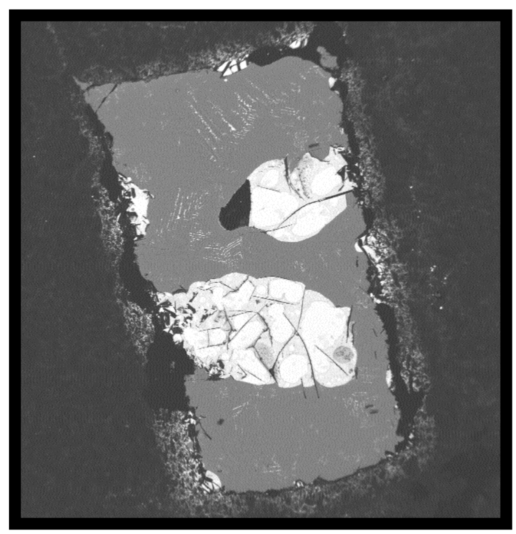
Work in the High Pressure Petrology Laboratory centers on processes important in the evolution of Mars interior and for the generation of the Martian meteorites. Laboratory experiments are combined with the study of actual meteorite samples in our research program. Some of the topics studied during the past year are described below.



Element partitioning between majoritic garnet and chondritic melt ***(Draper, Xirouchakis, Agee)***

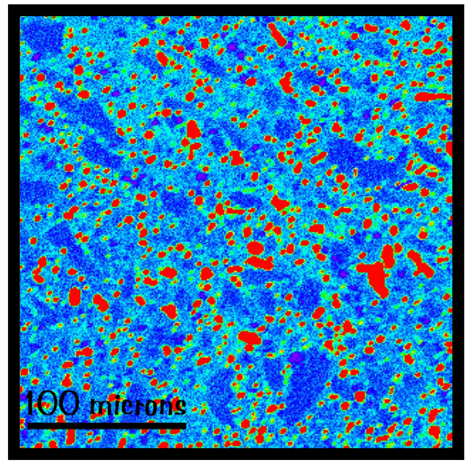
Measurements were made of how particularly useful trace elements, such as rare earth elements, distribute themselves between majorite, a high-pressure form of garnet, and melt having the approximate composition of ordinary chondrite meteorites. Such melts are thought to be good analogs for the Martian interior early in its history, and majoritic garnet is suspected of playing an important role in the geochemistry of the Martian meteorites. Our work shows how element partitioning begins to change as garnet undergoes the transformation to the higher-pressure majorite form, and these data are useful in understanding processes by which the Martian planetary interior has evolved over time. The image above shows a run product from one of these experiments. Additional work will extend to other useful trace elements and to higher pressures and temperatures where the transformation to majorite will go to completion.

Planetary core formation ***(Chabot, Agee)***



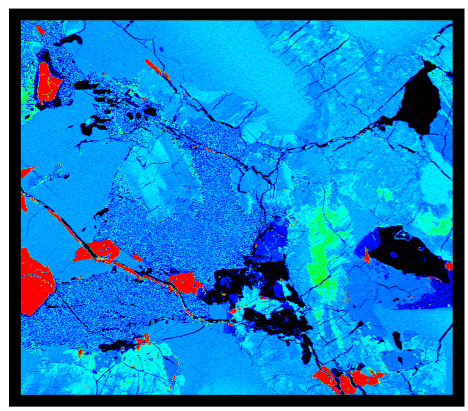
Formation of a metallic core is a basic process for all the terrestrial planets, large asteroids, and rocky moons. It is thought that core formation on the Earth and Moon resulted in depletions of vanadium, chromium, and manganese in their mantles. It may be possible to use the similarity between the Earth and Moon to constrain the material out of which the Moon formed. Systematic experiments were performed to evaluate this idea by measuring the partitioning of these elements between coexisting metallic and silicate melts. The image at right shows the result of one such experiment. The V, Cr, and Mn depletions can indeed be explained by a core formation event at high temperature, but the conditions needed to explain them differ from previous core formation models for the Earth. Future work combining these new data with those from other elements will help constrain the types of material out of which the Moon formed.

***Wetting of garnet-rich matrices by metallic and silicate melts* (Gilpin, Draper, Agee)**



Garnet's role in early Martian evolution could also be manifest in the way the planet's metallic core segregated and coalesced in the earliest stages of planetary formation. In order to help constrain this process, experiments designed to test whether metallic and silicate melts can migrate through a garnet-rich matrix were conducted. This was done by measuring the propensity for melts to form an interconnected network. The image at right shows the use of advanced image-mapping techniques using the ARES electron microprobe to characterize these run products. Our initial results suggest that metallic melts do not form an interconnected network in a garnet-rich matrix at moderate pressures, but that silicate melts might. Additional work remains to be done at higher pressures to examine this process further.

***Crystallization of Los Angeles, a shergottitic Martian meteorite* (Xirouchakis, Draper)**



Our study of Los Angeles, a recently discovered meteorite from Mars, showed how the final stages of crystallization of its parent magma produced complex features that can yield a wealth of information not just about this particular sample, but about other meteorites from Mars as well. The image at right is an X-ray map collected using the same advanced imaging techniques as in the specimen above, and illustrates the complexity of the subtle features under study. Our work showed that the intergrowth of tiny blobs of minerals, known as symplectite, is the breakdown product of an iron-rich pyroxene mineral and not another form as originally suggested. The study also showed how these late-stage features record a history of cooling and decreasing fugacity of oxygen that can be unraveled to assess the conditions that pertained at early stages of crystallization, and hence yield important information about the sample's parent magma. Many similar features have been misinterpreted to reflect parental conditions when in fact they record only the final stages, so it is important to "see through" these processes to the original conditions.

Unraveling the Complexities of Martian Meteorite EET79001

John H. Jones, Christopher Herd, Craig S. Schwandt, and James Papike [1]

Antarctic meteorite EET79001 is important to our understanding of Martian igneous processes. Experiments and calculations indicate that the temperature of the EET79001 magma was very high (~1300°C), making it a possible precursor for lower temperature, less primitive magmas. In addition, isotopic analyses indicate that EET79001 is a good candidate for a pristine melt of the Martian mantle. Unlike other Martian meteorites, such as Shergotty and Zagami, the EET79001 magma was minimally influenced by its passage to the surface through the thick Martian crust. For these reasons, it is important to understand the genesis of EET79001 in as much detail as possible.

A large obstacle to this understanding is that EET79001 contains "xenoliths," fragments of foreign material of olivine and pyroxene crystals. This means, for example, that a simple chemical analysis of the bulk rock does not represent the original magma composition. It is necessary to somehow subtract away the xenolith contribution to the bulk rock chemistry. This requires an understanding of how the xenoliths formed. Were the xenoliths dissolving and being incorporated into the EET79001 magma or were they acting as nucleation sites for crystallization as the magma cooled? The distinction is important. If the former was true then the xenolith subtraction process is somewhat easier. Anything that is a xenolith is culled. If the latter is true, then some of the "xenolith" is not really xenolith but actually crystallized from the original EET79001 magma and should not be subtracted. In this case some portions of the xenolith should be subtracted and some should not.

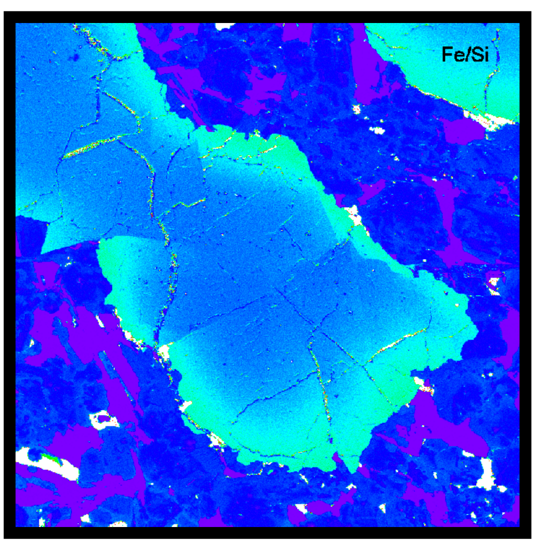


Figure 1. Fe/Si element ratio map of an olivine xenolith in thin section EETA79001, 68. Width of the image is 1.6 mm. The xenolith is medium blue, and extends from the center of the image to the upper left. The xenolith rim appears as light green, and its boundary with the groundmass (dark blue – purple) is quite sharp. Moreover, the sharp difference in color between the rim and the groundmass indicates a large difference in chemical composition. This, in turn, indicates that the xenolith rim did not form as an overgrowth on the xenolith core during crystallization of the groundmass.

The problem of xenolith origin has been approached via a two-pronged attack: experiments on an analog EET79001 composition and detailed elemental mapping of a polished section of the rock. This complementary approach has allowed us to gain greater confidence in the results of each individual method.

First, the compositions of crystals grown in our experiments were compared to the compositions of the rims of the xenolith crystals in EET79001. Olivine crystals grown in our experiments were very different in composition from xenolithic olivine rims in the rock. Conversely, pyroxene crystals grown in our experiments were actually very similar to pyroxene rims on the xenoliths. Thus, our working hypothesis was that the olivine xenoliths were "true xenoliths" and that only the cores of the pyroxene xenoliths were true xenoliths.

Next, elemental maps of the various kinds of xenoliths were made using the ARES electron microprobe. Figure 1 shows a map of Fe/Si ratio of an olivine xenolith. The xenolith stands out from the surrounding groundmass (quenched magma). The xenolith rim is of variable thickness and composition, the composition of the rim is markedly different from that of the groundmass minerals, and the boundary between rim and groundmass is sharp. Figure 2 shows the Fe/Si ratio map of a pyroxene xenolith (right side of figure). In contrast to the olivine xenolith, the pyroxene xenolith grades into the groundmass and the exact place that groundmass starts and xenolith ends is not clear. This supports our earlier hypothesis that the rims on the pyroxene xenocrysts grew from the EET79001 magma.

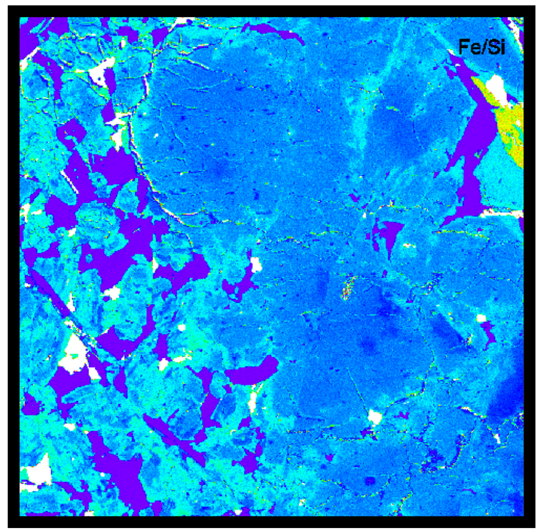


Figure 2. Fe/Si element ratio map of a pyroxene xenolith in EETA79001, 68. Width of the image is 1.5 mm. Warmer colors indicate higher Fe/Si values. Xenolith is the large medium blue region in the right portion of the image, and the groundmass is the fine-grained region comprising the left portion of the image. The xenolith rims are light blue to green, and are indistinguishable in color, and thus in chemical composition, from the groundmass pyroxene rims. This suggests that the xenolith rims represent overgrowths that grew from the molten groundmass on the outside of the xenolith cores during crystallization of the groundmass.

Our conclusion from these studies is that the bulk composition of the EET79001 magma requires some revision. Originally investigators deemed that all xenoliths were foreign and subtracted them. This approach was too simplistic. The EET79001 magma should contain more of a pyroxene component than has been previously recognized. This new approach makes us one step closer to unraveling the origins of this interesting Martian basalt and thereby, the evolution of the Martian mantle.

Re-Os Isotope Systematics of Martian Meteorites: Tracing the Origin of Highly-Siderophile Element Variation in Terrestrial Planets

Alan D. Brandon

Early planetary differentiation in the Earth and other planetary bodies consisted of internal melting and sinking of an iron-rich liquid to form the core, leaving a silicate mantle. Subsequent mantle melting and volcanism produced a basaltic crust. Variations in the ratios of siderophile elements, those that follow iron in geologic processes, are used to derive and test models for differentiation and core formation. In most cases it is not possible to measure the compositions of the core or mantle directly (iron meteorites that are asteroid cores are the exception), so they are inferred from the compositions of volcanic rocks derived from mantle melting over geologic time.

Rhenium (Re) and osmium (Os) are two highly siderophile elements, such that more than 99% of these elements are expected to reside in the iron-rich cores of Mars, Earth, and smaller terrestrial bodies. This should leave a residual silicate portion of the planet that is highly depleted in both elements relative to the original bulk planet, presumably of chondritic composition. Slight differences in the degrees of siderophile behavior for these two elements should also lead to highly non-chondritic Re/Os ratios. Furthermore, the radioactive decay of ^{187}Re to ^{187}Os (half-life 41.6 billion years) allows us to follow Re/Os variations over time by measuring ^{187}Os/^{188}Os ratios in volcanic rocks with different ages.

Measurement of Re-Os systematics in Earth rocks shows that its mantle has much higher concentrations of Re and Os than predicted by core formation alone. Furthermore, the ^{187}Os/^{188}Os ratio is the same as chondritic meteorites, indicating that it has not varied over much of Earth’s history. Thus, the Earth’s present-day mantle not only has higher than predicted Re and Os abundances, but has a time-averaged Re/Os ratio that is unfractionated from the original material that formed the Earth prior to core formation. These two observations combined are inconsistent with the siderophile element budget of the silicate portion of the Earth that is predicted by low-pressure core formation models. This paradox continues to be debated, and many alternative models have been proposed. These include inefficient core formation, core formation where extraction of the metal from the silicate residue occurs at greater depths in the Earth, or the possibility that the siderophile element budget in the Earth's mantle was modified by late accretion of chondritic material following core formation (the late veneer model). All of these models fail at some level, although the consensus by most workers presently is that a late veneer model has the best chance of explaining the siderophile element budget. Whichever of these models (or alternative

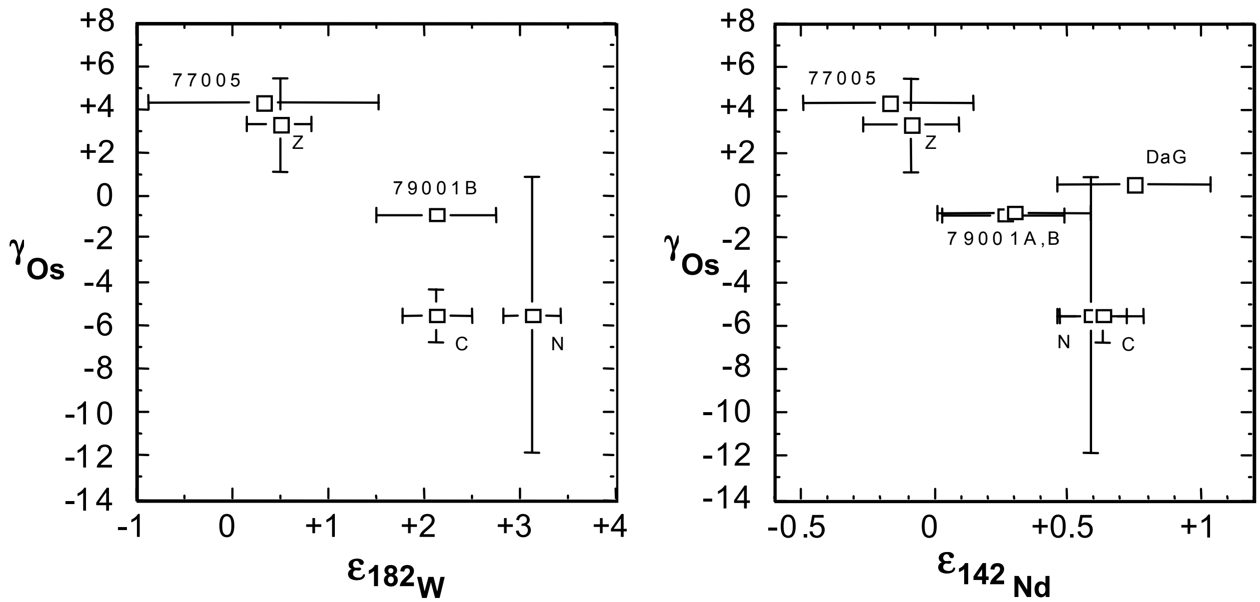


Figure 1. Os-W-Nd isotopic data for Martian meteorites (from Brandon et al. (2000), Geochim. Cosmochim. Acta 64, 4083-4095). Error bars are 2 σ.

models) turns out to be correct will reveal key constraints on the processes that acted during the earliest differentiation history of terrestrial planets to produce the chemical variations we observe presently for these elements.

The study of siderophile elements and Re-Os isotope systematics will also provide a better understanding of the role of the late veneer in bringing volatiles and organic materials to the surfaces of terrestrial planets, and thus has important ramifications to understanding the conditions that are conducive to life.

One of the key limitations to constraining siderophile element variation by studying Earth is that our planet has had 4.5 billion years of dynamic evolution that has potentially smeared out the chemical records of early differentiation. Mars on the other hand has had a restricted dynamic history. Compelling evidence from isotopic studies of Martian meteorites demonstrates that they have indeed retained chemical records of processes going on in their parent body (presumably Mars) during the first 100 million years of planetary formation. The measured initial Os isotopic variation (Figure 1, shown as γ_{Os} - % deviation of $^{187}Os/^{188}Os$ from average chondrites) in some of the Martian meteorites shows correlations with isotopic variations of other non-siderophile elements, ^{182}W and ^{142}Nd (derived from "short-lived" isotopes ^{182}Hf and ^{142}Sm that have half-lives in millions of years). This correlation indicates that the variation in Os isotopes could have only been established very early in Martian planetary differentiation because the parent isotopes of ^{182}W and ^{142}Nd are *effectively* decayed away after a few hundred million years. These correlations cannot be accounted for by simple models of core extraction and early melting (leading to crustal formation) in the interior of Mars, and likely result from isolation of cumulates in a Martian magma ocean consequent to core extraction. It should be noted however that the range in Os isotopic variation in these Martian meteorites overlaps those for chondritic meteorites (potential candidates for late veneer materials), and those for the present day Earth mantle. Hence, it is well possible that these data are best explained by a late veneer hypothesis, where the siderophile elements are replenished in the Martian mantle after core formation. Hence, magma ocean-cumulate and late veneer models are both consistent with the Os isotopic data obtained to present.

Given the large error bars and the potential of Re addition or loss during alteration on the Earth's surface for some of these Martian meteorites, additional work is needed to more precisely determine their Os isotopic compositions at the time of crystallization. Thus work on Os isotopic in Martian meteorites will continue, with the goal of addressing these problems. It is anticipated that new isotopic data will be up to 3 times more precise than previous work owing to state of the art advances in the new thermal ionization mass spectrometer at JSC on which these measurements will be performed. These new Os and Nd data, in combination with new and more precise W isotopic data presently being obtained at ETH-Zurich and previously published Sr and Nd data, will allow for better constraints on the origin of the earliest differentiation history of Mars. In addition it will be possible to more precisely address the role of a late veneer in establishing the siderophile and volatile element histories of the terrestrial planets.

Mars Soil Genesis Project

Richard V. Morris and Douglas W. Ming

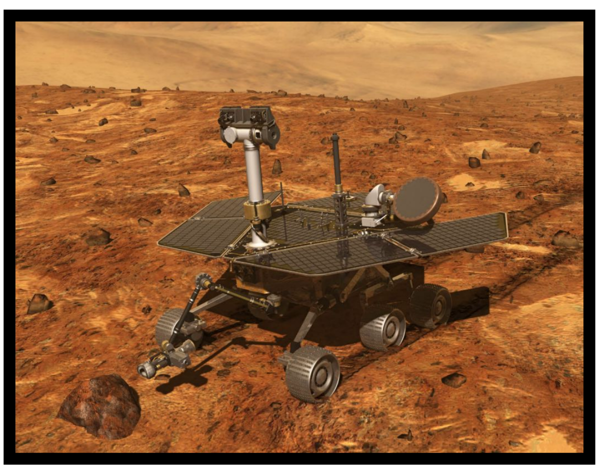
The Mars Soil Genesis Project (MSGP), centered at ARES JSC, is a sample and remote sensing based, multi-disciplinary, and multi-institutional project to study the mineralogy, chemistry, and mode of origin of Martian soil through time with reference to the processes or soil-forming factors that are responsible for its development from unconsolidated parent material. The project has five main goals: (1) collection, curation and characterization of Martian analog samples, (2) exploration of the mineralogical and chemical composition of the Martian surface by remote sensing observations, (3) exploration for inorganic explanation for putative biomarkers in planetary materials, (4) evaluation of Martian surface materials and analogs in support of future human Mars missions, and (5) exploration of the mineralogical and chemical composition of the Martian surface and the processes that modified it through time through synthesis of data obtained from Martian property or process analog materials, Martian remote sensing, and Martian simulation experiments.

Collection, curation, and characterization of Mars analog samples

Martian analog samples include (1) terrestrial samples that have certain properties (e.g., visible and near-IR reflectance spectra) that are similar to corresponding properties for the Martian surface as we understand them from remote sensing or by examination of Martian meteorites and (2) terrestrial samples that are formed by processes (e.g., meteoritic impact and hydrothermal alteration) that are known or inferred to have occurred on Mars. The ARES Mars Analog Sample Repository curates over 2,000 Martian analog samples that are used by project members for the scientific study of Mars. The samples are primarily basaltic in composition (because the surface of Mars is a basaltic world) and range in mineralogical composition from unaltered to highly-altered mineral assemblages.

The ARES MSGP laboratories contain a wide variety of equipment for physical separation of rocks and soils into constituent components and for instrumental analysis. Instrumentation includes X-ray diffraction, visible and near IR-spectroscopy, Mossbauer spectroscopy, vibrating sample magnetometer, magnetic susceptibility meter, and differential scanning calorimeter.

The MSGP is furnishing well-characterized Mars analog samples for validation of the performance of flight instruments being built for robotic planetary missions. These missions include the European Mars Express mission and NASA's CONTOUR, Mars 2003 MER, and Mars 2005 MRO missions.



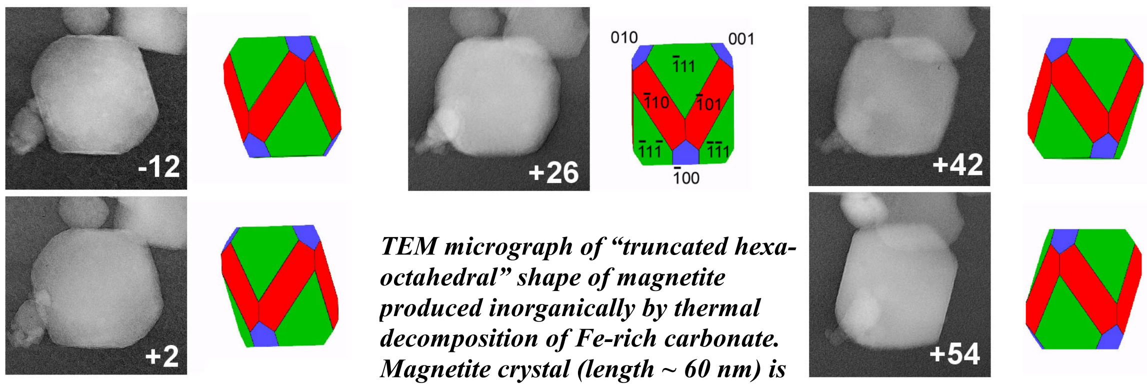
The Mars 2003 MER rovers will collect mineralogical and chemical data on the Martian surface in 2004.

Mineralogical exploration of Mars by remote sensing

The mineralogical and chemical composition of Mars is known through analyses of Martian meteorites and through remote sensing from the Earth, Martian orbit, and the Martian surface. ARES MSGP personnel participate directly in remote sensing observations of Mars as Co-Investigators in the Hubble Space Telescope guest investigator program, the ESA 2003 Mars Express mission (Beagle-2 lander), and the NASA Mars 2003 MER and Mars 2005 MRO missions.

Inorganic explanations for putative biomarkers in planetary materials

The MSGP project recently reported the first laboratory synthesis of unique crystal morphology for magnetite ("truncated hexa-octahedral" magnetite) that corresponds to the magnetite produced by magnetotactic bacterial strain MV-1 and that is reported for some magnetite crystals in Martian meteorite ALH84001. Thus, this magnetite in the meteorite may have been formed by inorganic processes rather than by biologic processes as suggested by others.



TEM micrograph of "truncated hexa-octahedral" shape of magnetite produced inorganically by thermal decomposition of Fe-rich carbonate. Magnetite crystal (length ~ 60 nm) is tilted through 66° rotation.

Support of human missions to Mars

The MSGP supports future human missions to Mars by recommending and supplying Mars analog materials for engineering and plant growth studies.

Mineralogical and chemical composition of Mars through time

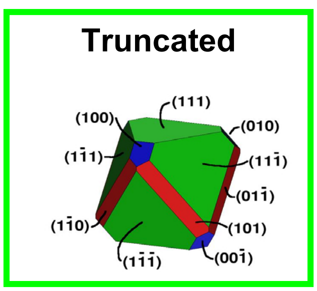
The end scientific goal of the MSGP is to characterize the mineralogical and chemical composition of the Martian surface through time and understand the process or soil-forming factors that were responsible for its development with time. This includes the role played by water (and its potential implications for life) in the mineralogical evolution of the planet. Studies by the project team have lead to important findings on the identification and distribution of hematite on the Martian surface.

Truncated Hexa-Octahedral Magnetites: Biosignatures in Terrestrial Samples and Martian Meteorite ALH84001

Kathie Thomas-Keprta, Simon J. Clemett, Susan J. Wentworth, David A. McKay, Everett K. Gibson

In 1996 our research team suggested that the fine-grained magnetite (Fe_3O_4) located within Fe-rich rims surrounding the carbonate globules in the Martian meteorite ALH84001 were the fossil remains of Martian microbes. Magnetite crystals produced by terrestrial magnetotactic bacteria strain MV-1 have been compared with a subpopulation of magnetites from ALH84001. Both are chemically and physically identical—specifically, both are single-domain, chemically pure, and exhibit an unusual crystal habit described as truncated hexa-octahedral. On Earth such truncated hexa-octahedral magnetites are only known to be produced by magnetotactic bacteria. It is suggested that the observation of truncated hexa-octahedral magnetites in ALH84001 is both consistent with, and in the absence of terrestrial inorganic analogs, likely formed by biogenic processes.

ALH84001 and MV-1 magnetite crystals were extracted from carbonate globules and cells, respectively, and analyzed by transmission electron microscopy (TEM). Magnetite crystal dimensions and habit were calculated from TEM observation of individual magnetites at multiple tilt angles, while chemical analyses were performed using energy dispersive x-ray spectroscopy (EDX).

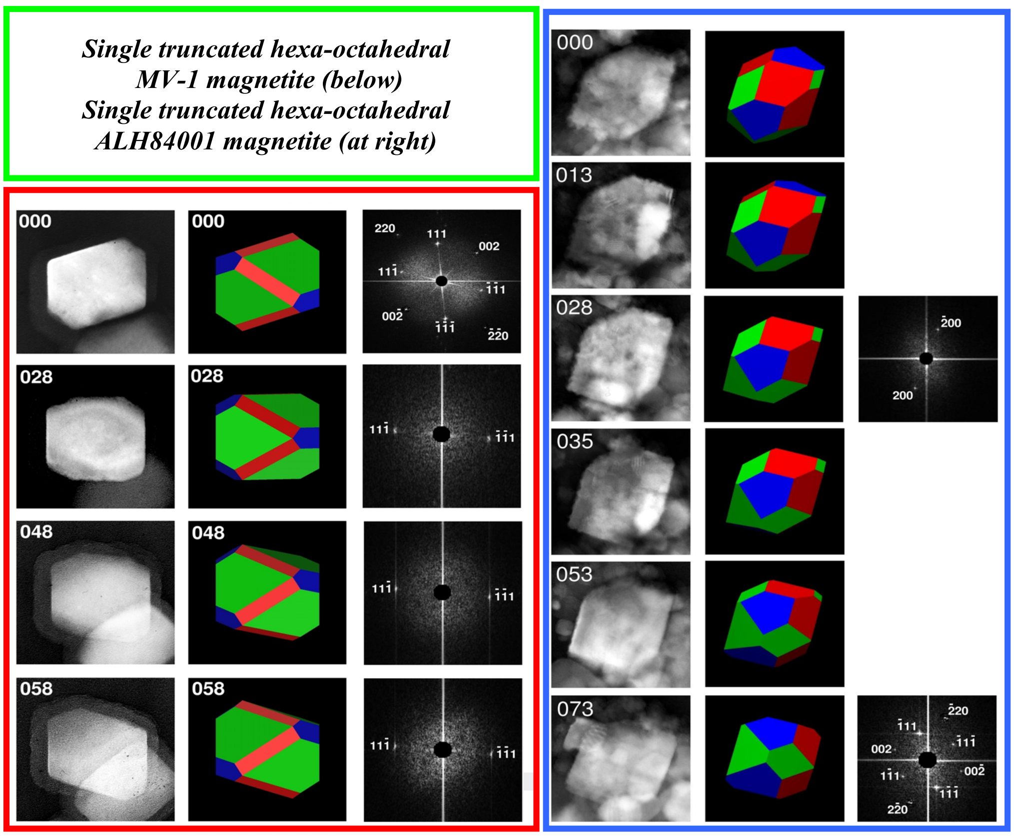


Idealized Truncated hexa-octahedral crystal habit of magnetite.

Six specific properties of biogenic magnetite from the magnetotactic bacteria strain MV-1 can be identified that when met collectively, constitute a rigorous biosignature (i.e., one that is not produced by natural inorganic processes). These are: (1) narrow size-range (i.e., single-domain for uniform magnetization) and shape (restricted width-to-length (W/L) ratios); (2) chemical purity; (3) few crystallographic defects; (4) truncated hexa-octahedral morphology (Fig 1.); (5) elongation along the [111] axis; and (6) alignment in chains within cells. These properties all act to optimize the interaction of the magnetites with a magnetic field. Since the strength of magnetic field interactions are much smaller than thermal energies kT, on thermodynamic grounds alone, chemical and biological processes cannot be influenced by magnetic fields to any measurable degree. Hence the six characteristics, outlined above, have *evolved* through the process of natural selection. No published reports of inorganic truncated hexa-octahedral magnetites are known.

The ALH84001 truncated hexa-octahedral magnetite crystals are found embedded in ~3.9 Ga old carbonate globules that fill cracks and pore space. Approximately 25% of the ALH84001 magnetites display 5 of the 6 properties described previously. Since our extraction procedure destroyed spatial relationships, the presence of aligned magnetite chains could not be evaluated (furthermore, such chains are rarely preservered after cell death). While the Martian truncated hexa-octahedral magnetite crystals are indistinguishable from those produced intracellularly by magnetotactic bacterium strain MV-1 (see figure), they are both chemically and physically distinct from the remaining ~75% of the magnetites in ALH84001. These other magnetites appear analogous to terrestrial inorganic magnetites. Intimate mixtures of both biogenic and abiotic magnetite crystals are observed in terrestrial samples of both recent and ancient carbonates.

Truncated hexa-octahedral magnetites on Earth are exclusively the product of biogenic activity — no natural or synthetic inorganic process is known that could explain the observation of truncated hexa-octahedral magnetites in a terrestrial sample. Unless there is an unknown and unexplained inorganic process on Mars, which is conspicuously absent on



A truncated hexa-octahedron is elongated along one of the [111] zone axes and displays eight {111} octahedral (green), six {110} dodecahedral (red), and six {100} cubic (blue) faces. Example of a single truncated hexa-octahedral MV-1 magnetite examined under incremental TEM stage rotation (red box). Magnetite at 000° is viewed down the [1-10] zone axis. At 058° (~60° rotation) the same magnetite is now viewed approximately down the [-101] zone axis (mirror image of crystal at 000°). Rotation axis is perpendicular to the plane of the page and aligned vertically. Example of a single, truncated hexa-octahedral ALH84001 magnetite, extracted from carbonate, and rotated a total of 73° (blue box). At 073°, the crystal is viewed down the [110] zone axis. Rotation axis is perpendicualr to the plane of the page and inclined ~20° to the right of the vertical. Note the {100 }and {110}faces are expressed to a greater degree than observed for MV-1 magnetite example shown here.

the Earth, it is suggested that ALH84001 truncated hexa-octahedral magnetites are formed by a mechanism similar to its terrestrial biogenic counterpart. *As such, these crystals are interpreted as Martian magnetofossils and constitute evidence of the oldest life yet found*.

In support of this, early Mars likely had freestanding bodies of liquid water, both organic and inorganic carbon (e.g., atmospheric CO_2), energy sources, and likely possessed a planetary magnetic field that would have been sufficient to support the growth of magnetotactic bacteria.

Life Beneath Glacial Ice - Earth (!) Mars (?) Europa (?)

Carlton C. Allen, Stephen E. Grasby[1], Teresa G. Longazo, John T. Lisle and Benoit Beauchamp[1]

Members of the ARES Astrobiology group are investigating a set of cold springs that deposit sulfur and carbonate minerals on the surface of a Canadian arctic glacier. The spring waters and mineral deposits contain microorganisms, as well as clear evidence that biological processes mediate subglacial chemistry, mineralogy, and isotope fractionation. The formation of native sulphur and associated deposits are related to bacterially-mediated reduction and oxidation of sulphur below the glacier. This non-volcanic, topography-driven geothermal system, harboring a microbiological community, operates in an extremely cold environment and discharges through solid ice.

Canadian cold spring

Microbial life can thus exist in isolated geothermal refuges despite long-term subfreezing surface conditions. Earth history includes several periods of essentially total glaciation. Ice in the near subsurface of Mars may have discharged liquid water in the recent past. Cracks in the ice crust of Europa have apparently allowed the release of water to the surface. Chemolithotrophic bacteria, such as those in the Canadian springs, could have survived beneath the ice of “Snowball Earth”, and life forms with similar characteristics might exist beneath the ice of Mars or Europa. Discharges of water from such refuges may have brought to the surface living microbes, as well as long-lasting chemical, mineralogical, and isotopic indications of subsurface life.

[1]*Geological Survey of Canada, Calgary, Alberta, Canada T2L 2A7*

Astromaterials Acquisition and Curation Office (ST)

Carlton C. Allen, Ph.D., Manager
http://curator.jsc.nasa.gov/

JSC and the Curatorial team are responsible for the curation of NASA's current collection of astromaterials that includes lunar samples collected by the Apollo astronauts, meteorites collected in Antarctica, cosmic dust collected in the stratosphere, and hardware exposed to the space environment. Curation comprises initial characterization of new samples, preparation and allocation of samples for research and education, and clean, secure storage of samples at JSC or remote sites. The foundations of our curation are the specialized cleanrooms (class 10 to 10,000) for each of the four types of materials, the supporting facilities, and the people, many of whom have been doing detailed work in ultraclean environments for many years.

The Curatorial team is also preparing to curate the next generation of extraterrestrial samples. JSC has been designated as the curation site for solar wind (Genesis), comet (Stardust), and asteroid (MUSES-C) samples collected by future NASA and international spacecraft missions. ARES is also leading the planning for post-mission sample handling and curation of samples returned by future Mars missions. In preparation for the Genesis mission, ARES built two new class10 cleanrooms where a dedicated team cleaned and assembled the collector payload. (See figure above.) It was then integrated into the spacecraft and launched in August 2001, and will be returned to the Genesis lab for curation in 2004. The Curatorial team has hired new staff and is conducting research and development of advanced concepts for curating all of these new sample collections.

The following reports give updates on curation of current astromaterials collections and plans for future collections.

Astromaterials Curation

Curators: Carlton Allen, Gary Lofgren, David Mittlefehldt, Michael Zolensky

Astromaterials curation is the cornerstone of the NASA Cosmochemistry research program. ARES staff curates the existing collections and distributes them to researchers worldwide to investigate the origin and evolution of the solar system.

Lunar Samples

Gary E. Lofgren, Andrea B. Mosie and Linda A. Watts

Lunar Sample Laboratory

The Apollo astronauts collected 2196 Moon rock and soil samples having a total mass of 382 kg. They are the only documented samples yet returned from another body in the solar system. JSC Astromaterials staff curates this national treasure in the Lunar Sample Facility, a suite of class 1000 cleanrooms and secure vaults constructed in 1979. The collection now comprises approximately 100,000 subsamples, many of which are located in research laboratories and museums worldwide. The bulk of the collection, including pristine samples and material returned following analysis, is stored at the JSC facility. Even 30 years after the Apollo missions, lunar sample research is active, with new techniques yielding new insights into the history of the Earth-Moon system.

Antarctic Meteorites

David W. Mittlefehldt, Cecilia E. Satterwhite and Kathleen McBride

Antarctic meteorite collection

Meteorites are rocks from space that have fallen on Earth. Since 1976, the U.S. has sent yearly expeditions to Antarctica to recover meteorites. (Glacial movement concentrates meteorites on icefields near mountain ranges.) The Antarctic Meteorite Program is a collaboration between the National Science Foundation (NSF), Smithsonian Institution, and NASA in which NSF is responsible for collection and NASA and SI share curation duties. ARES' role is initial description, temporary storage, and distribution of samples to investigators. This is performed in a dedicated suite of cleanrooms that were upgraded from class 10,000 to class 1000 during 2001. The meteorites are eventually sent to the Smithsonian Institution for permanent storage after demand for an individual sample has decreased, but JSC curates over 4,000 specimens at any one time. The number of new samples collected by a single field team and delivered to JSC each year has ranged from approximately 200 to well over 1000, including five meteorites from Mars and eight from the Moon. The 2001-2002 team returned 336 new meteorites from the ice.

Cosmic Dust

Michael E. Zolensky and Jack L. Warren

Microscopic particles of comets and asteroids, captured by the Earth and suspended in the stratosphere, are collected by dedicated equipment on two NASA aircraft. The collectors are prepared at JSC, and returned to the JSC Cosmic Dust Laboratory, a class 100 cleanroom, where individual particles are retrieved, documented, and distributed to researchers. The Cosmic Dust program has operated since 1981.

Space-Exposed Hardware

Michael E. Zolensky, Jack K. Warren and Thomas H. See

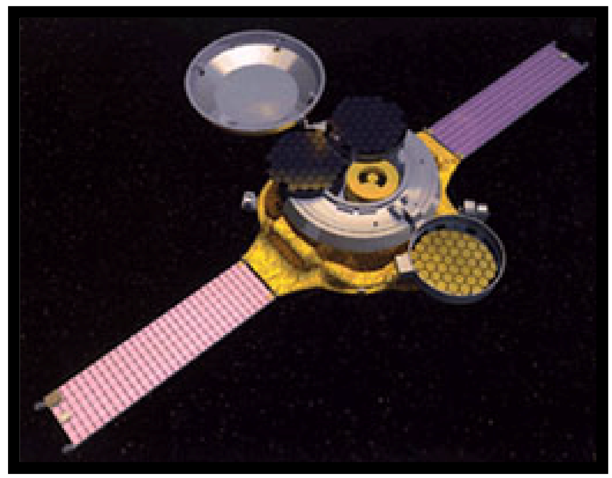
Since 1970, JSC has prepared and distributed a diverse collection of materials that have been exposed to the space environment. These have included pieces of the Surveyor 3 spacecraft sampled by the Apollo 12 astronauts, the Long-Duration Exposure Facility, several commercial satellites retrieved by the Space Shuttle, and materials from the Mir space station. Curation of these materials is done in the Facility for Optical Inspection of Large Surfaces.

Genesis — Solar Wind Sample Return

Eileen K. Stansbery

Genesis is a spacecraft mission to collect atoms and ions of the solar wind, the extended atmosphere of the Sun. When it returns to Earth in 2004, Genesis will bring NASA's first spacecraft-collected samples since Apollo 17 in 1972, and the first ever material returned from deep space. ARES curation personnel are essential members of the Genesis Science Team. ARES responsibilities are contamination control and curation. To accomplish these tasks JSC built two ultraclean class 10 cleanrooms, NASA's cleanest laboratories. In 2000 the Genesis payload was dismantled, cleaned, and reassembled in these special cleanrooms (see photo in curation overview).

After its August 2001 launch, the Genesis spacecraft began its journey sunward. It is now in a stable orbit at a point in space, about 1 million miles from Earth in the direction of the Sun, where the gravities of Earth and the Sun balance. The spacecraft has unfolded its collectors and will "sunbathe" for two years, collecting atoms from the solar wind.



Genesis spacecraft

Genesis carries four instruments: bicycle-tire-sized solar-wind collector arrays, made of materials such as diamond, gold, silicon and sapphire, and designed to entrap solar wind particles; an ion monitor, to record the speed, density, temperature and approximate composition of the solar wind ions; an electron monitor, to make similar measurements of electrons in the solar wind; and an ion concentrator, to separate and focus elements like oxygen and nitrogen in the solar wind into a special collector.

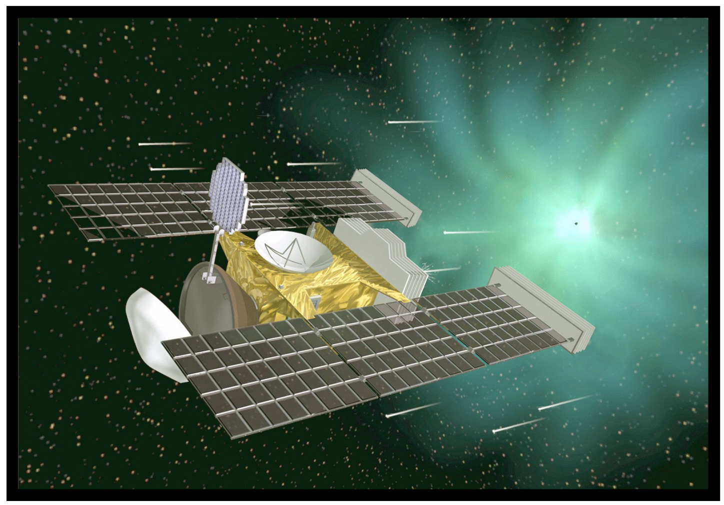
Sample collection will conclude in April 2004, when the spacecraft begins its return to Earth. In September of that year, the samples will arrive on Earth in a dramatic helicopter capture. As the sample-return capsule parachutes toward the ground in Utah, specially trained helicopter pilots will catch the capsule in midair to prevent the delicate samples from being disturbed by the impact of a landing.

This treasured sample of the Sun will be opened, processed, and preserved in the JSC Genesis laboratory, and distributed for study to scientists in the next decade and over the next century. The atoms and ions will help scientists understand the composition of the original solar nebula that formed the planets, asteroids, comets and the Sun we know today.

Michael E. Zolensky and Friedrich P. Horz

Comets are believed to be the oldest, most primitive bodies in the solar system, possibly comprised of some of the basic building blocks of life. They contain the remains of materials from the formation of stars and planets, holding volatile, carbon-based rich elements that are likely to provide clues about the nature of the building blocks of our solar system. Importantly, they may provide evidence that comets brought water to the Earth, Mars and other worlds, making life possible.

With the prospect of comets offering this treasure house of ancient information, there is significant anticipation about what findings scientists will be able to extrapolate from a firsthand examination of cometary materials. Because the Stardust spacecraft will both return samples of material from a comet's dusty coma, and provide real-time in-flight data about what it encounters, there is a real possibility of scientific findings that will change the way we view our origins.



Stardust spacecraft

The Stardust spacecraft was launched in February 1999. It has already made one gravity assist at Earth and now is heading for a second such maneuver. In January 2004, the spacecraft will fly about 100 km in front of the nucleus, through the halo of gases and dust at the head of comet Wild 2. During this passage the spacecraft will collect dust and volatiles. The comet samples are expected to consist of ancient pre-solar interstellar grains and nebular condensates that were incorporated into comets at the birth of the solar system.

In addition to the cometary samples, the spacecraft is also collecting interstellar grains (stardust) during the cruise phase of the mission. This stardust flows into our solar system in a great river of dust and gas. Analysis of this material will permit us to greatly expand our knowledge of the evolution of stars, the birth of the chemical elements, and the history of our galaxy. This mission was the first sample return mission launched in 30 years and it collected the first material from deep space, yet because it is traveling a much greater distance than its sister Genesis mission, it will return two years later with its precious cargo.

ARES scientists are key members of the Stardust Science Team. They helped develop and test the silica aerogel that is the magic material that will capture and hold the comet coma grains. This team has developed exacting techniques for the removal and analysis of captured grains from the silica aerogel. With the spacecraft drawing ever nearer its January 2004 encounter with the comet, these scientists are also designing the JSC curation lab which will receive the samples in 2006, and planning the preliminary analyses which will for the first time reveal the true nature of comets, their role in the early history of the solar system, and possibly, the origin of water and organic matter on Earth and Mars.

MUSES-C — Asteroid Sample Return

Michael E. Zolensky and Faith Vilas

The MUSES-C mission will be the first sample return mission by Japan's space science agency, The Institute of Space and Astronautical Science (ISAS), and is being developed jointly with NASA. The goal of the mission is to return chipped samples from the surface (regolith) of a small near-Earth asteroid called 1998 SF36.

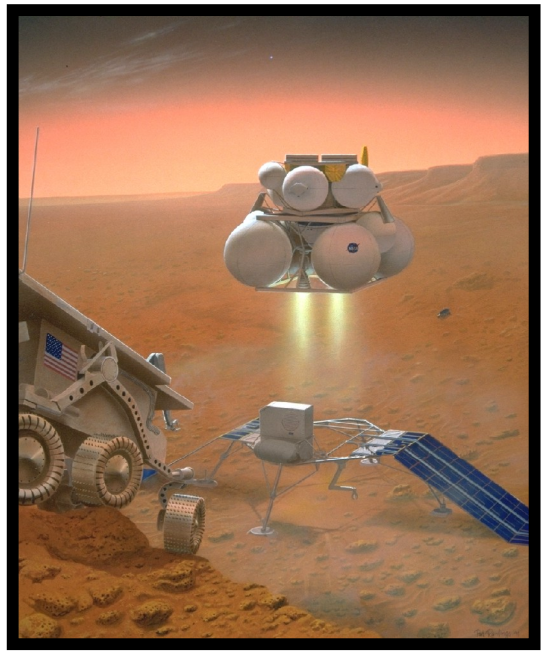
Muses-C spacecraft

The spacecraft will leave Earth in January 2003, and rendezvous with the near Earth asteroid in 2005. Once in orbit, a very small rover will drop from the spacecraft, and roll around on the asteroid's surface making measurements and observing the collecting activities. The entire spacecraft will briefly touch down on the surface 2 or 3 times. During each of these touch-and-go landings a projectile will be fired at the surface at a velocity of a 300 m/s, which will blast free a small quantity of material. This liberated sample could be powder if there is an asteroidal regolith, or chips if bedrock is exposed. In any case, on the order of 1g of material will be collected into a horn-shaped receptacle at each of three different sites.

In July 2007 the samples will be returned to Earth within a hermetically-sealed capsule, and flown to the ISAS lab for 1 year of preliminary investigation in Japan. Following this period the samples will be made widely available, with approximately 10% of the sample mass coming to JSC for curation and distribution. ARES scientists are members of the Muses-C Science Team and are involved in both sample curation and characterization of the target asteroid (see Planetary Astronomy report).

David J. Lindstrom and Carlton C. Allen

NASA's Mars Exploration Program will eventually include robotic sample acquisition missions to return samples to Earth for detailed study, probably sometime in the middle of the next decade. The Astromaterials Acquisition and Curation Office is working to prepare for all of the activities to be done once the sample-containing spacecraft returns to Earth, ranging from recovery of the spacecraft to ultimate distribution of samples to scientists for study.

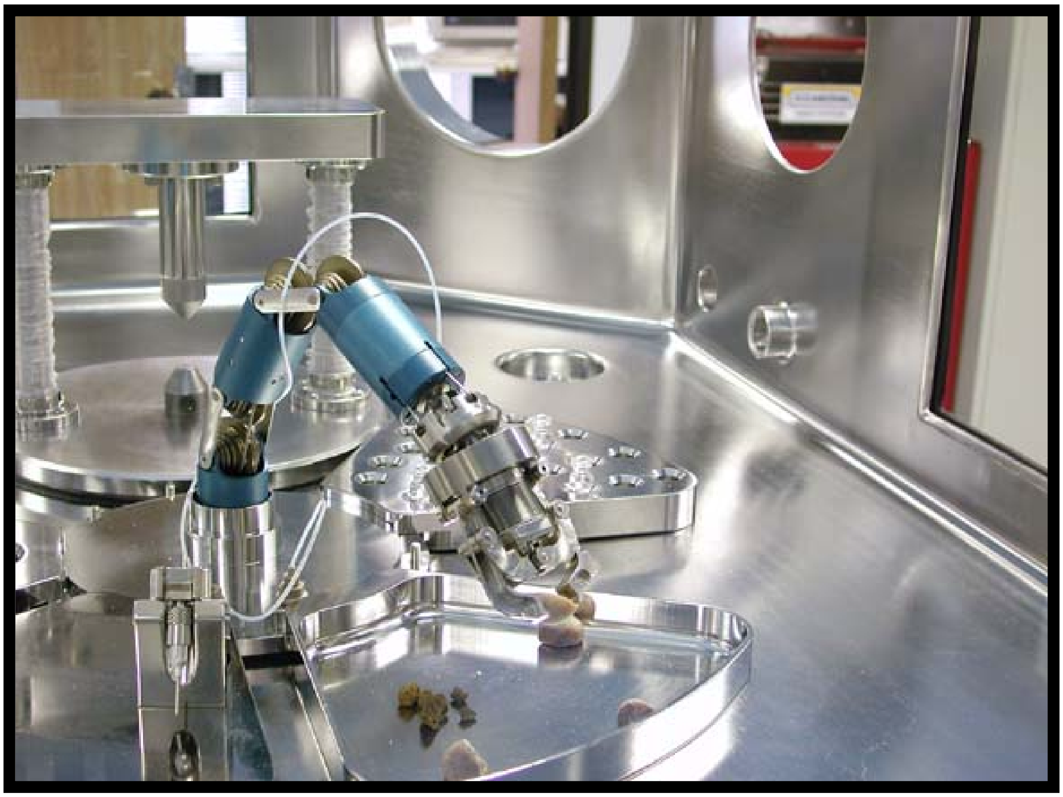


Mars sample return concept

One of the strong scientific reasons for returning samples from Mars is to search for evidence of current or past life in the samples. Because of the remote possibility that the samples may contain life forms that are hazardous to the terrestrial biosphere, NASA's Planetary Protection Officer (guided by a National Research Council study) has specified that all samples returned from Mars must be kept under strict biological containment until tests show that they can safely be released to other laboratories. It is also important to ensure that scarce or subtle traces of Martian life not be overwhelmed by contamination with terrestrial microbes. Thus, the facilities used to contain, process, and analyze the samples must have levels of biological and chemical cleanliness that are unprecedented in high-level biocontainment facilities.

In planning for the processing of Mars samples, the ARES curation staff is building on its experience in preliminary characterization, hazard testing, and distribution of lunar, meteorite, and cosmic dust samples to scientists worldwide. Unique requirements for the processing of Mars samples have inspired an active program to develop sample handling techniques that are much more precise and more reliable than the approach (currently used for lunar samples) of using human hands in nitrogen-filled gloveboxes. Individual samples from Mars are expected to be much smaller than lunar samples, the total mass of samples returned by each mission being 0.5-1 kg, compared with many tens of kg of lunar samples returned by each of the six Apollo missions. Smaller samples require much more processing to be done under microscopic observation. In addition, the requirements for cleanliness and high-level containment would be difficult to satisfy while using traditional gloveboxes.

JSC has constructed a laboratory to test concepts and technologies important to future sample curation. The Advanced Curation Laboratory includes a new-generation glovebox equipped with a robotic arm to evaluate the usability of robotic and teleoperated systems to perform curatorial tasks. The laboratory also contains equipment for precision cleaning and the measurement of trace organic contamination.



Robotic arm in glovebox

Human Exploration Science Office (SX)

Wendell W. Mendell, Ph.D., Manager
http://ares.jsc.nasa.gov/HumanExplore/intro.html

The Human Exploration Science Office conducts Earth and space science research, planning, and support for human space flight. The office includes several distinct groups, having very different technical responsibilities.

The planetary exploration group focuses on the science to be done during future human exploration of the Moon, Mars, or asteroids. They represent the science "customer" in mission planning exercises. Their work involves planning and modeling geologic and biologic investigations as well providing input to forums on space policy.

The Earth science group manages the database of astronaut images of Earth, trains and debriefs astronauts on geology-geography, conducts Earth science research, and shares this information with the public through their award-winning web site. The image science group analyzes Shuttle and International Space Station mission imagery and researches all anomalies. They have resolved issues raised during missions and have provided data on the state of the Hubble Space Telescope.

The space debris function involves two separate groups. Members of the orbital debris team are some of the world's top experts in modeling and monitoring debris in Earth orbit. They construct complex mathematical models for describing and predicting the debris environment in Earth orbit. The hypervelocity impact test facility team designs and assesses debris shielding for spacecraft. They also use environmental models to evaluate risks to spacecraft, including the Space Shuttle and the International Space Station.

Reports on several projects are given in the following pages.

Earth Science Aboard ISS

Gregory J. Byrne and Kamlesh P. Lulla

A major milestone was reached during 2001 with the long awaited start of Crew Earth Observations from the International Space Station (ISS). This heralds a new era for ARES Earth Science Group, whose missions are to provide astronaut images of Earth for a broad range of science, commercial, and outreach applications and to engage the public in the excitement of human exploration of Earth from space.

Lake Sarez (top), deep in the Pamir mountains of Tajikistan.

Thousands of images were returned from ISS, catalogued, and made available to the public over the web (http://eol.jsc.nasa.gov), adding to our database of over 400,000 earth images from the Space Shuttle. The public's enormous and growing appetite for the images was demonstrated by our web metrics for the year. By the end of 2001, over one million web hits per month were logged, a figure that has nearly doubled since ISS imagery started coming on-line at the beginning of the year. Web hits were recorded from over 70 countries around the world, and over 100,000 images per month are downloaded. About one-fourth of all hits were from .com or .edu domains.

One remarkable early finding is the high-spatial resolution of about 6 m achieved in ISS images found by our earth sciences staff, a significant improvement over previous astronaut imagery and approaching the highest resolution of color images available from commercial satellites. Also, the ISS and Space Shuttle images are now routinely digitized as 3-band color data and georeferenced for scientific analysis. In doing so recently, we demonstrated that astronaut-acquired imagery compares favorably with Landsat data for remote sensing classifications in land-use and vegetation. These new developments enhance the image database as a research resource for both primary data on the state of the Earth and for secondary data to supplement remote sensing information from other sources.

While a new chapter for Earth Observations was opened with the start of ISS operations, the chapter on its successful predecessor, Shuttle-Mir Earth Observations, was closed with the publication of a compilation of the Shuttle-Mir Earth science results   Also, the Earth Sciences staff was active in outreach activities, highlighted by regular submissions to NASA's popular *Earth Observatory* web site (http://earthobservatory.nasa.gov).

The decline in health of coral reefs worldwide has gained international attention, and the Earth Sciences staff is deeply involved with research into this global problem. We are applying shuttle and ISS images of coral reefs in conjunction with Landsat data for discriminating between clouds and reef structure; an important process for the reef mapping. The staff also contributed images and consultation to a 2001 United Nations publication, World Atlas of Coral Reefs. In addition, a staff proposal "Using Landsat 7 Data in a GIS-based revision of ReefBase (A Global Database on Coral Reefs and Their Resources)" was selected for funding by NASA Headquarters (Code Y).

Thunderstorms with glaciated anvil tops

During 2001, the Earth Sciences staff completed a heavy load of astronaut crew "Earth smart" training. The training highlighted scientific themes, such as human impact on the environment, global change in climate, health of coral reefs worldwide, changes in ice packs and glaciers, changes in river deltas, and accumulations of atmospheric aerosols. Upgrades to the Earth Observations Lab continue to strengthen operations. Two important mission support upgrades were completed: configuration of the Earth Science console in the Mission Control, Telescience Support Center, and implementation of the Satellite Tool Kit's state vector propagation software for STS and ISS tracking, the latter resulting in more accurate orbit timing for the Earth photo targets identified in the uplink flight notes to the crews. Operations for ISS are currently progressing smoothly.

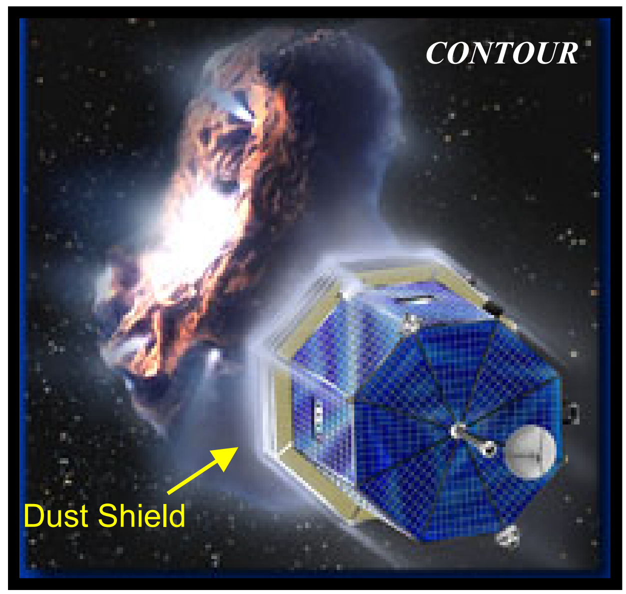
The compact Italian city of Venice with its renowned canals.

Shielding Spacecraft from Hypervelocity Impact

Eric L. Christiansen and Jeanne L. Crews

The U.S. Destiny Laboratory Module and the Joint Airlock were launched and incorporated into the International Space Station (ISS) during 2001. All elements of the ISS face risks from puncture by impacts from orbital debris or from micrometeorites. Both of these modules are protected by hypervelocity shielding designs invented and developed by the Hypervelocity Impact Technology Facility (HITF) personnel in ARES. The shields are the most advanced shielding designs available and contain Nextel ceramic cloth and “bullet-proof” Kevlar fabric as well as the standard aluminum outer-bumper and inner pressure-shell. The ISS International

HITF Shielding protects the U.S. Laboratory module on ISS.



Contour Dust Shield consists of 4 Ceramic cloth bumpers and a Kevlar rear wall.

Partners also use the HITF shielding to protect the ESA Columbus Module (ELM) and the Japanese Module (JEM).

The John Hopkins Applied Physics laboratory has chosen another of the HITF shield designs to protect the Comet Nucleus Tour (CONTOUR) spacecraft that is scheduled for launch in 2003. HITF personnel also provided feasibility studies, analysis, and tests for CONTOUR shielding. HITF personnel hold patents for many of their shielding inventions.

Kira Jorgensen

When most people think of orbiting objects, intact, operating satellites come to mind. In addition to these operating satellites, there are approximately 10,000 objects in low Earth orbit (LEO) that are larger than 10 cm in diameter and an even higher number of objects smaller than 10 cm. In order to characterize the space environment, the physical characteristics of orbiting objects are taken into consideration and these properties are used in current space environment models and the building of shields for spacecraft, as well as in providing base work for future environment studies. Some of these characteristics, including material type, are currently assumed. Using low-resolution reflectance spectroscopy, and comparing absorption features and overall shape of spectra it is possible to determine material types of man-made orbiting objects in both low Earth orbits (LEO) and geosynchronous Earth orbits (GEO).

When a satellite is launched into a specific orbit, rocket bodies (R/Bs) carrying the sufficient propellant are left in various orbits. Since most R/Bs are homogeneous material, they are ideal objects for testing. NASS (NASA AMOS Spectral Study) began observations in May 2001 collecting data for eight nights. Data were collected on twenty-two rocket bodies (R/Bs) using the 1.6-meter telescope at Air Force Research Laboratory (AFRL) Maui Optical Supercomputing (AMOS) site and the results were compared to a laboratory database of spacecraft material.

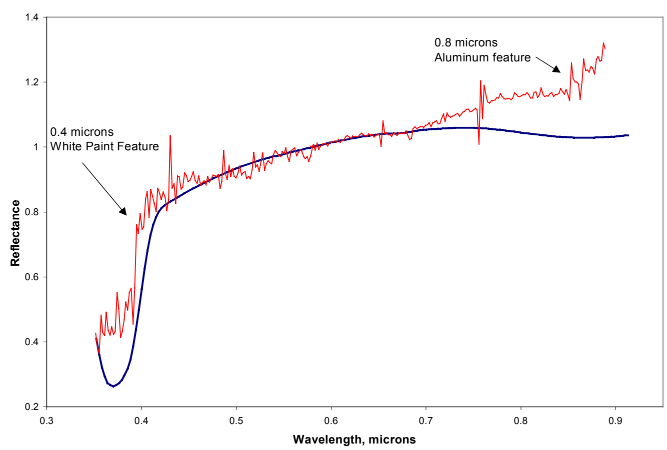


Figure 1. LEO R/B spectra compared to a Laboratory Sample of Flown White Paint from LDEF.

Each material type shows a different spectrum based on its composition. Figure 1 shows the reflectance spectrum of a LEO R/B (shown in blue with more noise) overlaid with laboratory samples (in red and smoother) in an attempt to characterize the material. The feature near 0.4 microns is due to white paint. Near 0.84 microns is a strong aluminum feature. This rocket body is identified as aluminum coated with white paint.

In addition to determining the material type of orbiting objects, NASS can be used to evaluate the degradation of intact satellites. R/Bs with similar paint schemes will exhibit similar spectral

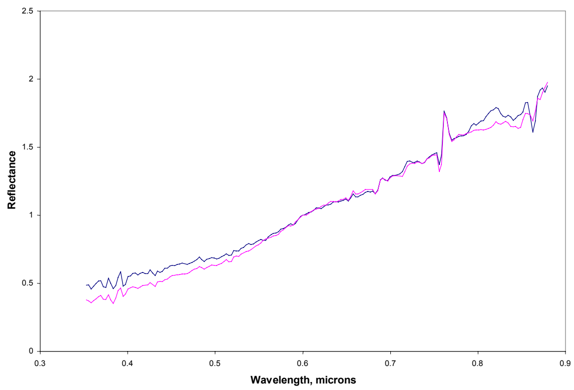


Figure 2. Similar R/Bs Observed on the Same Evening

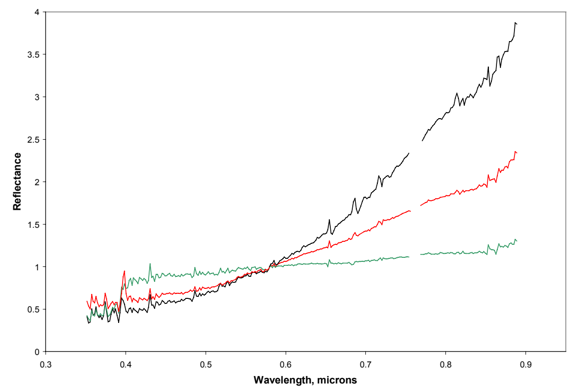


Figure 3. Three different R/Bs Observed on the Same Evening

features, but the characteristic reflectance can change with exposure to the space environment. Figure 2 shows a comparison of two similar R/Bs launched five years apart but not exhibiting significant differences in the spectrum. The absorption features are located in similar positions and the shapes of the spectra are very similar. Figure 3 shows three different R/B's observed on the same evening. Here, we see that R/B's composed of differing materials can be distinguished.

More observations are scheduled using the 1.6-meter telescope at AMOS as well as with the 3.67-meter telescope at the same site. As more observations of R/Bs, intact satellites, large debris fragments, and eventually, smaller debris are accumulated, it will be possible to determine whether the effects of space weathering and other age-dependent factors can be measured with this technique.

Statistical Measurements of the Orbital Debris Environment

Eugene G. Stansbery

Orbital debris is a concern for all present and future space-faring nations. The U.S. Space Command tracks orbiting objects larger than about 10-cm. diameters. Objects much smaller than this size can damage operational spacecraft because of the high relative velocities between orbiting objects (average collision velocity = 10 km./sec.) The ARES Space Debris Research Group statistically measures the debris environment for objects smaller than 10 cm.

Radar Measurements

NASA has used the Haystack Observatory, including both the Haystack and HAX radars, since 1990 to sample the debris environment at low Earth orbit (LEO) altitudes. The Haystack radar is a high power, X-band (3-cm wavelength) radar with very high sensitivity. It is capable of detecting debris as small as 0.5 cm diameter at an altitude of 500 km. HAX can detect 2 cm diameter debris at 500 km. Rather than tracking individual objects, these radars are used in a non-tracking, or "staring," mode which allows debris to pass through the radar's field of view. The rate at which objects are detected can then be related to the density or flux of particles in orbit. NASA collected 600 hours of data from each of the two radars in FY2001. A new report is in preparation and planned for release in 2002.

The Haystack (large dome) and Haystack Auxiliary (HAX) Radar (small dome) located in Tyngsboro, Massachusetts, northwest of Boston.

Optical Measurements in LEO

There is anecdotal evidence that some population of debris appears bright optically but appears small or invisible to radar. To characterize this population, NASA has built a zenith-staring Liquid Mirror Telescope (LMT). The mirror for this telescope consists of a 3-meter diameter parabolic dish that holds several gallons of liquid mercury. The dish is spun at a rate of 10 rpm. Centrifugal force and surface tension causes the mercury to spread out in a thin layer over the dish creating a parabolic reflective surface, accurate to within a fraction of the wavelength of light. NASA has used the LMT to collect 392 hrs of optical observations. A report was published in April 2001, on data collected through July 2000.

Liquid mirror telescope

Optical Measurements in GEO

NASA is also statistically sampling the debris environment at near geostationary altitudes (GEO). NASA collected data for 437 hours on a 0.3-m CCD Debris Telescope (CDT), co-located with the LMT. A CDT report was published in August 2001.

NASA is collaborating with the University of Michigan operating its 0.6/0.9-m classical Schmidt telescope located at the Cerro Tololo Inter-American Observatory, Chile. The facility is capable of detecting a 10cm object at GEO, assuming an albedo of 0.2. Approximately 11 nights of data were collected in FY2001 while evolving data collection and analysis techniques.

Albedo and Spectroscopy

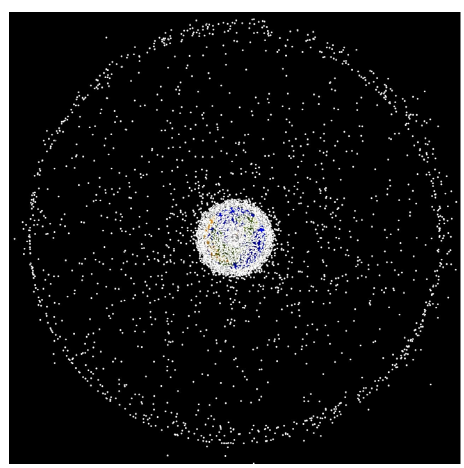
NASA is currently teamed with the Air Force Research Laboratory (AFRL) Maui Optical Site (AMOS) trying to improve the optical albedo model for small debris.

Spectroscopy is valuable in determining the composition of space debris. NASA has collected spectral data using instrumentation at AMOS on rocket bodies and satellites in preparation for extrapolating the technique to small space debris. (See material identification report.)

Improved Orbital Debris Environment Model

Nicholas L. Johnson

Understanding the particulate environment in near-Earth space is essential to the design and operation of both human-operated and robotic spacecraft. Whereas models describing the natural meteoroid environment have been available for many decades, not until the 1980's was it possible to begin a similar definition for man-made objects, which now exceed meteoroids in low Earth orbits, i.e., below 2000 km. NASA JSC has been the Center of Excellence for this work since such efforts began.

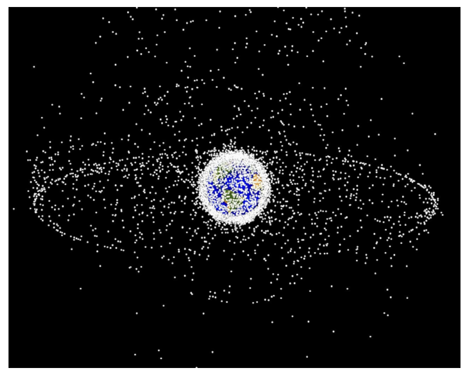


This computer graphic indicates the position of nearly 10,000 man-made objects now in orbit about the Earth. The outer ring depicts the geo synchronous orbital regime near 36,000 km altitude above the equator.

The earliest environment models were inadequate to support the needs of large, complex spacecraft like the Space Shuttle and the International Space Station. Therefore, in 1991 and 1996 more comprehensive orbital debris environment models were developed. In 2001 the Space Debris Research Group of ARES completed development of a fundamentally new, more capable model called ORDEM2000 (Orbital Debris Engineering Model, 2000).

ORDEM2000 improvements over previous models are primarily three-fold. First, the new model is based upon a much broader and complete foundation of environment measurements and analyses. Thousands of hours of observations of near-Earth space from ground-based radar and optical sensors were collected during the 1990's on objects as small as 2 mm. The population of particles smaller than 1 mm was discerned from the examination of spacecraft surfaces like the NASA Long-Duration Exposure Facility, the Hubble Space Telescope, and the Space Shuttle itself. In addition, special experiments have been deployed on spacecraft to record debris impacts, like NASA's Orbital Debris Collector on the former Mir space station.

Secondly, a fundamentally different approach was selected for ORDEM2000. The model is more empirically based and relies less on analytical expressions. Population growth terms are derived from the most current environment evolution models, principally the EVOLVE model developed by the ARES Space Debris Research Group. This is all made possible by the third major improvement to the model, namely taking advantage of the tremendous advances in computer technology, which have appeared since ORDEM96 was developed. The data storage and computational abilities of modern personal computers permit operations heretofore not possible except with special equipment.



This view of the Earth's satellite population is closer to the equator and illustrates a class of satellites that rise to high altitudes above the northern hemisphere.

Like its predecessor, ORDEM2000 will become the standard model for use in determining the vulnerability of Space Shuttle missions, the International Space Station, and a wide variety of NASA robotic spacecraft to the orbital debris environment. Several foreign space programs are also expected to employ ORDEM2000 for debris risk assessments.

International Guidelines for Mitigation of Orbital Debris

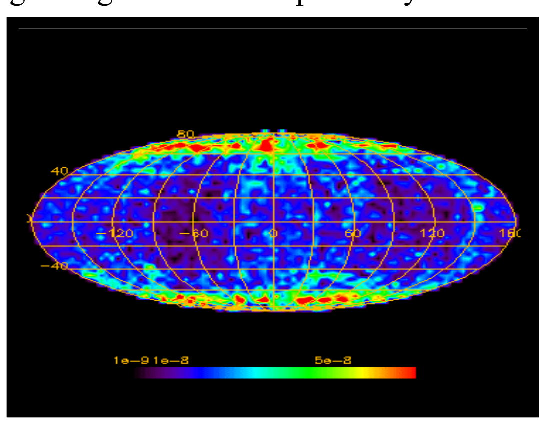
Nicholas L. Johnson

Since the launch of Sputnik 1 in 1957 worldwide space activity has led to the creation of millions of man-made objects in orbit about the Earth. Nearly 95% of the approximately 10,000 large satellites (greater than 10 cm in diameter) are non-functional spacecraft, expended launch vehicle stages, mission-related hardware, and fragments from on-orbit explosions or collisions. In 1995 NASA was the first space agency in the world to issue detailed guidelines designed to curtail the generation of debris in orbit about the Earth. Developed at JSC by the Space Debris Research Group, these guidelines became the basis for the U.S. Government Orbital Debris Mitigation Standard Practices, which were approved in the year 2000 by all U.S. agencies involved in space activities. The objective of both sets of guidelines is to prevent the unnecessary production of long-lived orbital debris through better space mission and space vehicle design, operation, and disposal.

Following the NASA lead, space agencies in Japan, Europe, and Russia have issued similar recommendations to national as well as commercial space efforts in their respective countries. In 1999 the Inter-Agency Space Debris Coordination Committee (IADC), whose membership includes the space agencies of ten countries and the Europe Space Agency, accepted the challenge to develop a consensus set of orbital debris mitigation guidelines. The scientists and engineers of the Space Debris Research Group have played a major role in this effort, providing both technical and policy assistance.

In February 2001, a U.S. proposal to the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space for the development of orbital debris mitigation guidelines for the broader international aerospace community was adopted. Under this plan, the IADC guidelines, which will be completed in 2002, will be presented to the United Nations in early 2003. Following a period of review and again relying heavily on ARES personnel, a UN-approved set of orbital debris mitigation guidelines is expected by 2004.

The spatial density or the number of objects in a given volume of space is increasing, with the greatest concentrations near the Earth's poles. International debris migration guidelines are designed to moderate the growth of the debris population.



Limitation of Risk from Reentering Satellites

Nicholas L. Johnson

This solid rocket motor casing was found in the Saudi Arabian desert after its fall to Earth on January 12, 2001.

Since the first man-made satellite reentered the atmosphere in December 1957, more than 17,000 known objects with masses varying from less than a kilogram to tens of tons have fallen uncontrolled back to Earth. The majority of these satellites completely disintegrated during reentry, and most of the surviving components from the remaining reentries fall harmlessly over the world's oceans. Although no serious personal injury or property damage has been identified with satellite reentries to date, large fragments of spacecraft and launch vehicles have impacted in countries around the globe, such as the nearly 300-pound solid rocket motor casing which fell onto the desert in Saudi Arabia in January 2001 or the 500-pound launch vehicle propellant tank which fell in South Africa in April 2000.

For many years, the NASA Space Debris Research Group has led the U.S. and the international aerospace community in evaluating the risks of uncontrolled satellite reentries and in promoting the mitigation of these risks. In the year 2000, this office conducted an extensive analysis of the risks posed by the contemplated disposal of more than 70 Iridium spacecraft for a Justice Department-led interagency working group. The orbital debris research team at JSC first established the 1 in 10,000 risk criterion now incorporated into NASA and U.S. government interagency guidelines.

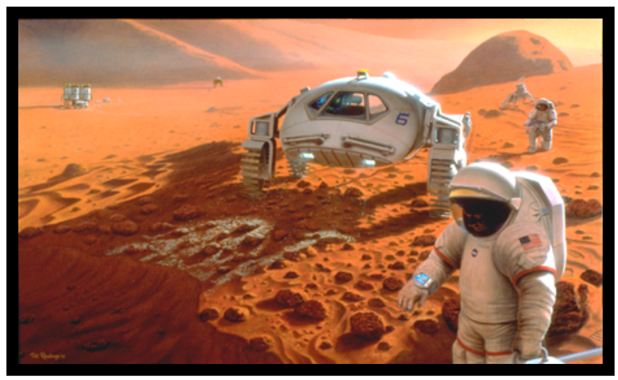
A complex physics model, developed jointly by NASA and Lockheed Martin personnel, is used to predict the survival or demise of each satellite component. The Object Reentry Survival Analysis Tool (ORSAT) also calculates the likely impact zone or footprint of the surviving debris from either controlled or uncontrolled reentries. Coupled with detailed world population density maps, ORSAT can determine the risk of human casualty resulting from an uncontrolled reentry.

If the satellite is of a size or design that would result in an unacceptable risk to people in the event of an uncontrolled reentry, NASA and foreign guidelines recommend a controlled reentry over a broad ocean area. In 2001 a member of ARES received a NASA Group Achievement Award from the NASA Administrator for his participation in the controlled reentry of the Compton Gamma Ray Observatory in June 2000. ARES personnel also served a critical role in support of the reentry of the Russian Mir space station in March 2001 and were instrumental in the establishment of an international communications network to exchange data and reentry predictions in the event of a significant reentry risk.

Science Planning for Future Human Planetary Exploration

Wendell W. Mendell

The Human Exploration Science Office in ARES partners with the Exploration Analysis and Integration Office of the Engineering Directorate in formulation of future scenarios for human exploration of space. The role of ARES in this relationship is to provide requirements for scientific activities on future missions and to represent the views of the scientific community during development of mission scenarios.



Since the announcement in 1996 by ARES scientists of possible signs of fossil life in a meteorite from Mars, discussions of future missions have been couched in the context of exploration of Mars. One feature of the resultant baseline mission scenario is a surface stay of approximately 500 days by the crew. While an extended surface stay challenges planners concerned with crew health and safety, the available time can be a boon to scientific objectives of the mission. ARES scientists have been working with mission planners to translate the opportunities for planetary science into crew timelines, equipment, and operating protocols.

As NASA works to formulate its overall planetary exploration strategy, questions arise as to the appropriate use of robotic missions vis-à-vis human missions for exploration. ARES scientists have worked with their academic colleagues in NASA-sponsored workshops to define the roles of humans and robots. A paper on the subject from this Office has been accepted for publication in the journal *Acta Astronautica*. Historically, the argument is often made that scientific goals can be satisfied exclusively by robotic missions. However, the most comprehensive strategy has a robotic component playing a complementary and supporting role to human missions. A human explorer cannot be matched in adaptability, insight, and hypothesis testing on site. Robots are best used for precursor characterization of exploration venues, for supporting humans in fieldwork, and for probing hazardous environments. Robotic exploration in isolation is limited by preconceptions of designers who are limited by technology and funding in their ability to respond to new findings once the mission parameters have been frozen. The Human Exploration Science Office strives to ensure the balance between these complementary modes of discovery.

ARES Education and Public Outreach

Marilyn M. Lindstrom
http://ares.jsc.nasa.gov/Education/outreach.htm

Sharing our science with the public is an essential part of ARES programs in earth and space science. As the small enclave of physical scientists at a NASA engineering and space flight center, our staff is frequently called upon to support presentation and interview requests to the JSC public affairs or education offices. Staff members are active volunteers in the JSC Speaker's Bureau, Distance Learning Outpost, Texas Aerospace Scholars, NASA Educator Workshops, National Engineers Week programs and support many local science fairs. Our scientists are frequent mentors for university faculty and students in programs sponsored by the NASA education or equal opportunity offices. Our participation in the JSC Open House offered 10 exhibits and a room full of educational activities to the 120,000 attendees.

Earth Observations E/PO

Education and outreach are significant parts of the Earth Observation efforts. Our earth science staff collaborates with the University of California, San Diego on the EarthKam program that allows for students in grades 5-12 to make earth observations from shuttle and ISS. ARES provides the scientific content and facilitates the astronaut photography. The staff also submits regular contributions to the educational journal Geography Review and NASA's Earth Observatory website.

Human Exploration E/PO

ARES exploration staff participates in many activities related to future human exploration of the Moon and Mars. They are frequent speakers at public and education venues on the topics of space farming, resource utilization, early outposts, colonization, and space policy. The intrinsic appeal of humans exploring the solar system is strengthened by our work in the technology of living on other worlds, and the science that they might do while there.

Planetary Science E/PO

Our long-term, planetary science education and public outreach programs are funded in association with NASA astromaterials and astrobiology research and Mars exploration. They involve partnerships between ARES scientists and educators at NASA, universities, school districts, and museums. Major products in 2001 included:

1) Astrobiology exhibit and education module to accompany a major Microbes exhibit at Space Center Houston
2) Fingerprints of Life? CD ROM/web site that contains classroom activities and resources
3) Space Rocks Tell Their Secrets activities and slideshow

Pat Rawlings image that provides the theme for the Astrobiology exhibit -Environments for Life, from the Deep Sea to Deep Space.

Our scientist/educator team introduced these products at 5 dedicated teacher workshops at JSC and teacher conferences. They also presented 35 additional workshops on Rocks from Space, Mars, and Solar System Exploration based on previously published education products. Other events included Sun-Earth Day at the Houston Museum of Natural Science and Eclipse 2001 at Space Center Houston.

ARES is also a major partner in two new initiatives that target women and minorities. As coinvestigator on an Office of Space Science Minority University Initiative grant to the University of Houston-Downtown, ARES staff trained student ambassadors and Houston teachers in space science activities, and mentored three minority student interns in research at JSC. As partners with the Solar System Exploration forum, ARES organized and presented space science activities for trainers in the Girl Scouts, USA.

Student ambassador presenting space science at Sun-Earth Day

Our efforts to communicate and inform have received recognition from the National Science Teachers Association in that both the Earth Observations and Astromaterials Curation web pages are included in the SciLinks program that connects textbooks to websites that appropriately enhance learning.

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ARES Award Recipients 2000–2001

External Honor Awards

Rotary Stellar Award
Richard V. Morris, Ph.D. (2001)

National Science Foundation Antarctica Service Medal of the United States of America
John Lisle, Ph.D. (2001)

NASA Honor Awards

Exceptional Service Medal
Gordon A. McKay, Ph.D. (2001)
Marilyn M. Lindstrom, Ph.D. (2000)

Group Achievement Award
Hubble Space Telescope Science Mission 3-A Team (2000)
Hypervelocity Impact Test and Analysis Team (2001)
Genesis Contamination Control & Curation Team (2001)
International Space Station AA Solar Array Repair Team (2001)

NASA Space Flight Awareness Awards

Space Flight Awareness Launch Award
Jonathan M. Disler (2001)

Flight Safety Award
Kevin Crosby (2001)
Michael Snyder (2001)

NASA Johnson Space Center Honor Awards

Certificate of Commendation
Eileen K. Stansbery, Ph.D. (2000)

NASA Goddard Space Flight Center Honor Awards

Group Achievement Award Hubble Space Telescope Service Mission 2

David Bretz

Group Achievement Award Hubble Space Telescope Service Mission 3A

David Bretz

Outstanding Commitment Award

David Bretz

Space and Life Sciences Directorate Awards

Special Recognition Performance Award

Laurence Nyquist, Ph.D.
Nicholas L. Johnson
Douglas W. Ming, Ph.D.

Scientific Sustained Superior Achievement

Herbert A. Zook, Ph.D. (posthumous)
Gregory J. Byrne, Ph.D.
Richard V. Morris, Ph.D.
Craig S. Schwandt, Ph.D. (LM)
Astromaterials Curation Team
ARES Astrobiology Magnetite Team
Mars Returned Sample Handling Team

Special Scientific Achievement

ARES Experimental Exobiology Team
Thermal Ionization Mass Spectrometer Laboratory Team
Genesis Contamination Control & Curation Team

Space Flight Sustained Superior Achievement

ISS Imagery Analysis Team
Earth Observations Team
Earth Observations Data Analysis International Space Station 1 & 2
Earth Observations Payload Development & Operations Support International Space Station 1 & 2

Special Space Flight Achievement

Orbital Debris Environment Team

Professional Sustained Superior Achievement

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Curatorial Laboratory Technical Support Team

Special Professional Achievement

Eileen K. Stansbery, Ph.D.
Advanced Curation Laboratory Team
Meteorite / Cosmic Dust Laboratory Upgrade Project Team

Director's Excellence Award

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Kimberly Cyr, Ph.D.
Judith H. Allton (LM)
Carol M. Schwarz (LM)
Jack L. Warren (LM)
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Justin H. Kerr

Going the Extra Mile (GEM) Award

Dana M. Lear
David Bretz
Donn A. Liddle
Sharon Milburn

Lockheed Martin Science Engineering Analysis and Test (SEAT) Awards

Top Flight Award

ARES Astrobiology Biomarkers Team

Top Flight Award – Honorable Mention

James Heydorn (SEAT Core Computer Systems Project Team)

Special Recognition Award

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Jerry H. Wagstaff
Craig Schwandt, Ph.D.
Claire Dardano
Jaclyn Allen
Julie Robinson, Ph.D.
Judith Allton
Robert Scharf
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Lightening Award (Monetary Award)

Jaclyn Allen
Judith Allton
Simon Clemett, Ph.D.
Kevin Crosby
Anita Dodson
Daniel Garrison
Gerald Haynes
James Heydorn
James Hyde
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Safety Award For Excellence (SAFE)

William Davidson
Charles Landrum

Science Engineering Analysis and Test (SEAT) Employee of the Month Award

D. C. Golden, Ph.D.

SEAT Commendation Award

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